UNCLASSIFIED: Distribution Statement A. Approved for public release


# *U.S. Army's Ground Vehicle Energy Storage R&D Programs & Goals*


TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

**Yi Ding, Ph.D**

**Energy Storage Team, US Army TARDEC**

**September 13, 2011**

**Disclaimer: Reference herein to any specific commercial company, product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the Department of the Army (DoA). The opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or the DoA, and shall not be used for advertising or product endorsement purposes.**

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

| 1. REPORT DATE | 2. REPORT TYPE | 3. DATES COVERED |
|---|---|---|
| **13 SEP 2011** | **N/A** | **-** |

| 4. TITLE AND SUBTITLE | 5a. CONTRACT NUMBER |
|---|---|
| **U.S. Army's Ground Vehicle Energy Storage R&D Programs & Goals** | 5b. GRANT NUMBER |
| | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER |
| **Yi Ding** | 5e. TASK NUMBER |
| | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| **US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000, USA** | **22262** |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR'S ACRONYM(S) |
| **US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000, USA** | **TACOM/TARDEC/RDECOM** |
| | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) **22262** |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release, distribution unlimited**

13. SUPPLEMENTARY NOTES
**The original document contains color images.**

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | |
| **unclassified** | **unclassified** | **unclassified** | **SAR** | **17** | |

# Agenda

- Goals & Mission
- Army Applications & Approach
- Challenges
- Battery Power & Energy
- Success Factors
- TARDEC Programs
- Advanced 6T Roadmap
- Failure Mechanism & Thermal Runaway
- Ballistic Test Results
- SBIR Portfolio & University Portfolio
- Battery Logistics Burden

# Energy Storage Goals and Mission

## Energy Storage Goals

- Develop **safe and cost** effective energy storage systems
- Reduce **battery weight & volume burden** (Increase Energy & Power Density)
- Reduce logistics and fuel burdens
- Extend **calendar and cycle life**
- Enhance performance and increase operating time (silent watch, etc)

## Energy Storage Mission

- **Develop** and **mature** advanced ES technologies for transfer to vehicle platforms
- Test & evaluate ES technologies for prequalification and to assess their TRL
- Identify **technology barriers** and develop technical solutions
- Provide technical support to customers, other teams and government agencies for all ES requirements
- Provide **cradle-to-grave** support for all Army ES systems

# Army Applications & Approach

- **Army Applications/Drivers:**

TARDEC - Ground

– Major Applications
  - Robotics
  - Survivability
  - Weapons Systems
  - Electromagnetic Armor (EM Armor)
  - Starting, Lighting and Ignition (SLI)
  - Hybrid Vehicle Acceleration and Silent Mobility
  - Silent Watch

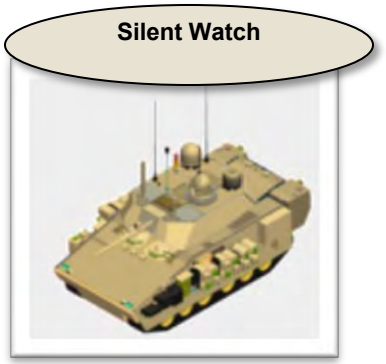
Hit Avoidance

Targeting Systems

– Approach
  - Standard Form Factor (6T)
  - Ultra-capacitor/Battery/Fuel Cell Hybrid Power Sources

# Challenges

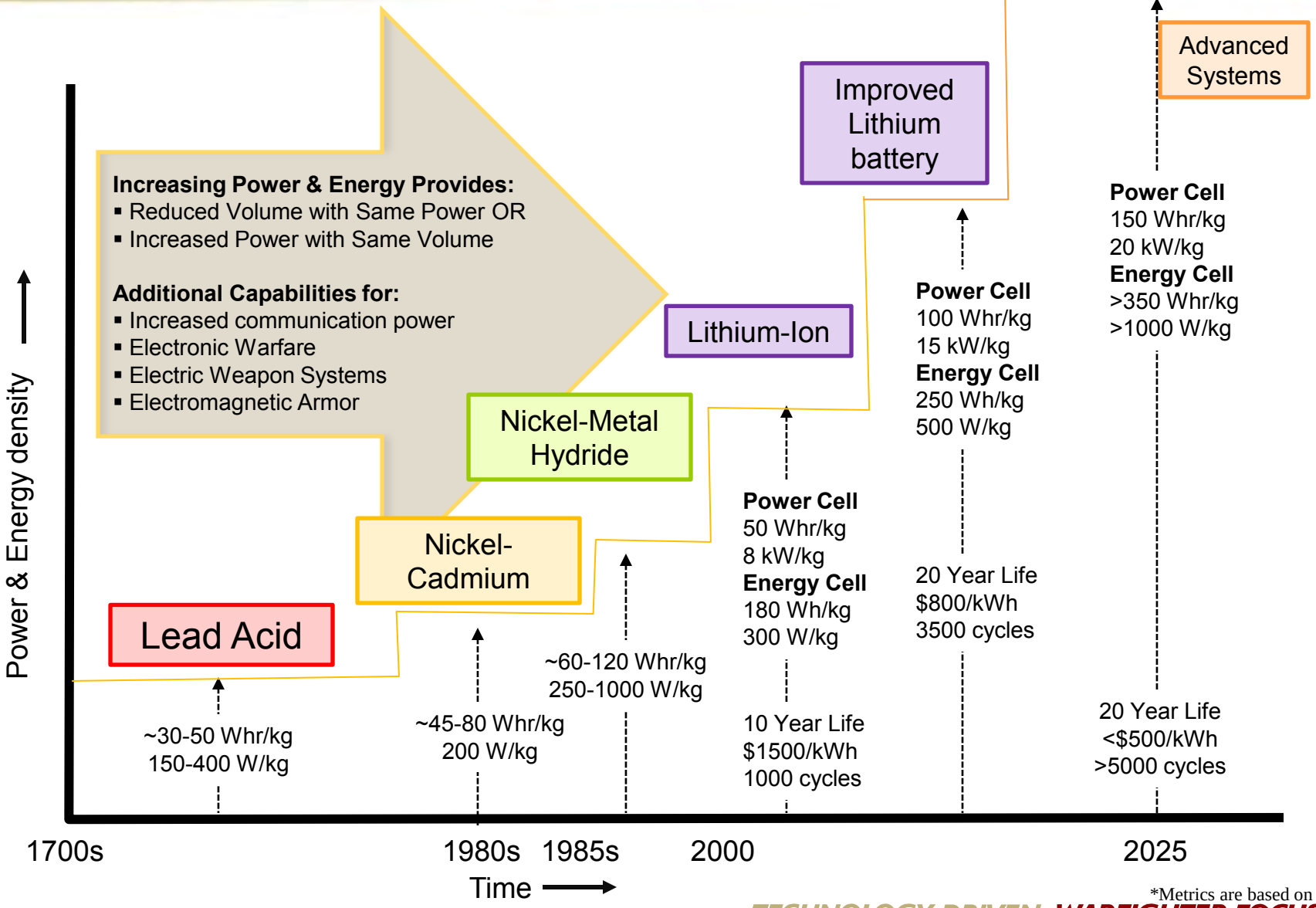
- **Operational issues**
  - – Wide operation temperature range
  - – Battery usage & limitations – energy & power density
  - – Demand for auxiliary power on-board vehicles
  - – Emphasis on silent (“quiet”) watch
  - – Unmanned vehicles (air/ground)




- **Safety**
  - – Thermal runaway

- **Cost**
  - – Limited service life
  - – High cost
  - – Increased emphasis on system power metrics (KPPs, low consumption components)

# Battery Power & Energy Versus Time (Technology Roadmap)

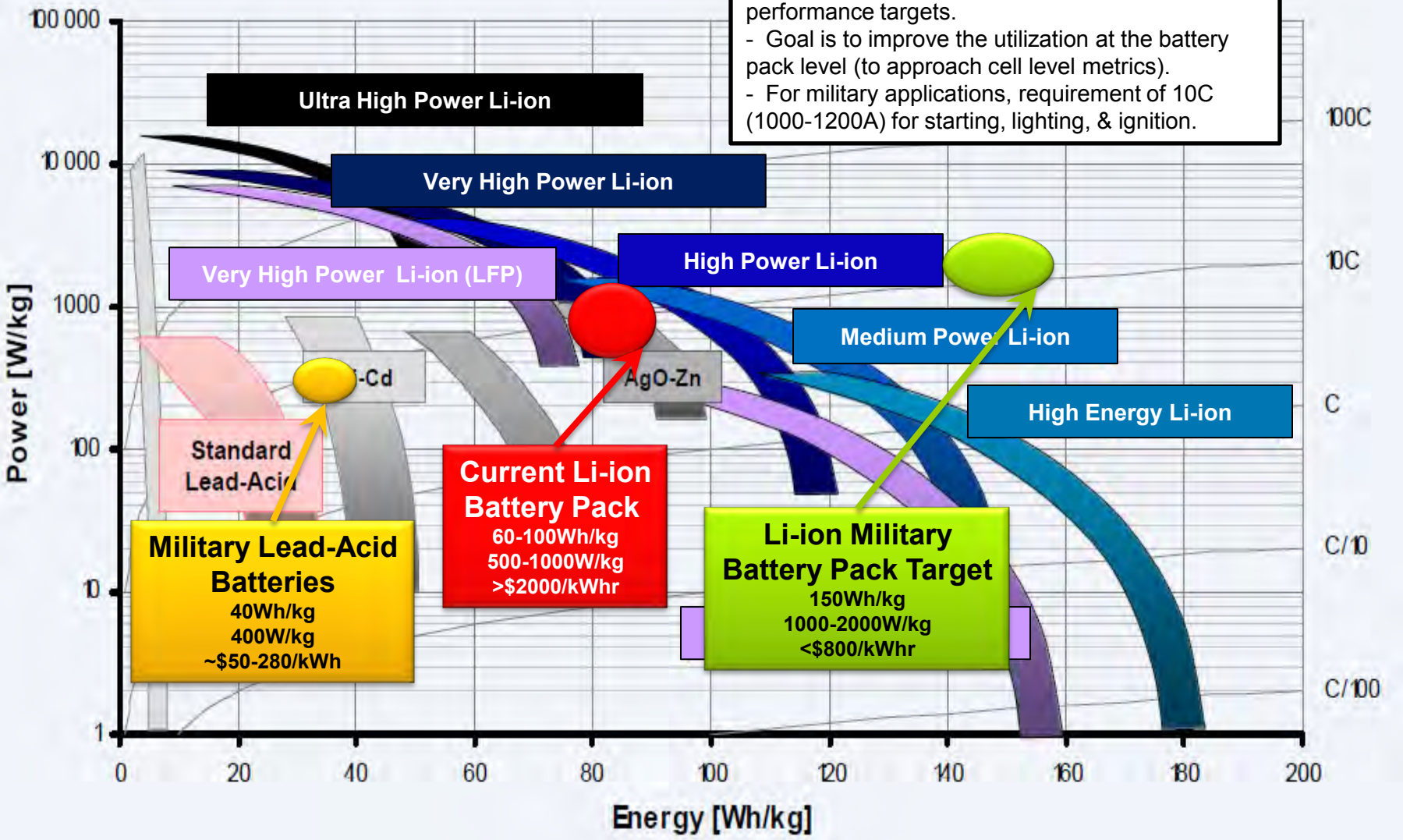



*Metrics are based on cell data

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

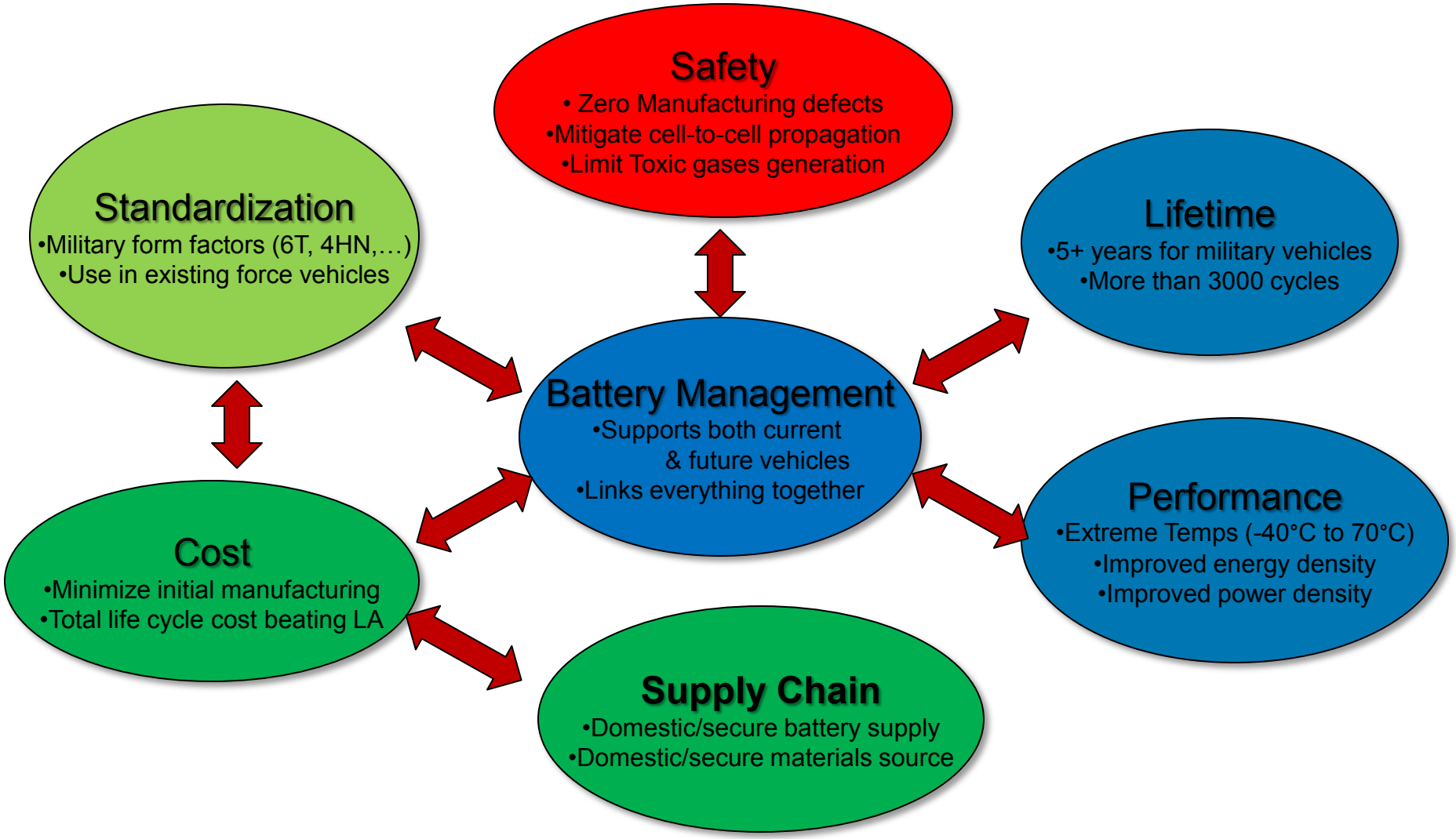
# Energy Storage Technology: Ragone Plot (with Military Pack Targets)

- Plot represents existing battery pack as well as performance targets.
- Goal is to improve the utilization at the battery pack level (to approach cell level metrics).
- For military applications, requirement of 10C (1000-1200A) for starting, lighting, & ignition.



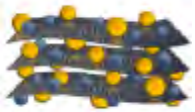
# Key Success Factors For Li-ion Battery Applications for Vehicles

Successful introduction of Li-ion Batteries depends on a number of factors:



# TARDEC Programs Functional Breakdown

## Energy Storage Functional Breakdown



### Basic Research

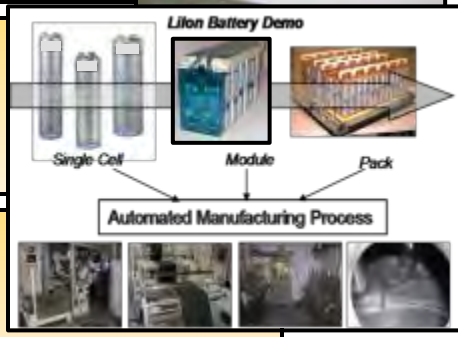
- Lithium plating phenomenon in Li-ion batteries
- **Study on the mechanism of thermal runaway in VRLA Batteries and Methods of Suppression**
- Study of electrode/current collector interface & safe separator for Li-ion batteries
- Development of high energy density anode materials for improved Li-ion batteries
- Alternative electrolyte for use in lithium-ion batteries (higher voltage, improved performance)

### Applied / Applications Research

- Electromagnetic Armor Power Maturation
- Nickel-Zinc 6T Battery Development
- **Development of 6T battery for SLI and silent watch using Li-ion chemistries**
- Absorbed Glass Matt lead acid battery for 24V military 4HN battery

### Manufacturing

- High Power, High Energy Density Li-Ion Battery Manufacturing Program
- **Lithium-Ion Cell/Battery Pack Manufacturing**
- Advanced battery material scale-up facility




### Battery Management / Safety

- **In-House BMS evaluation for PM HBCT & new laboratory**
- Universal BMS using novel algorithms for battery health
- Ballistic and abuse tolerance studies on cells, module and packs
- Development of advanced diagnostic tools for cycled cells

### Alternative Systems

- Hybrid Power Module
- Lithium-Titanate Hybrid Vehicle Pack Integration
- **Characterization of ultra-capacitors for SLI and high power applications**

TARDEC has over 60 Projects & Programs

# Advanced 6T Battery Roadmap

**Military Lead-Acid 6T Batteries**
40Wh/kg
400W/kg
~$100-280/kWh

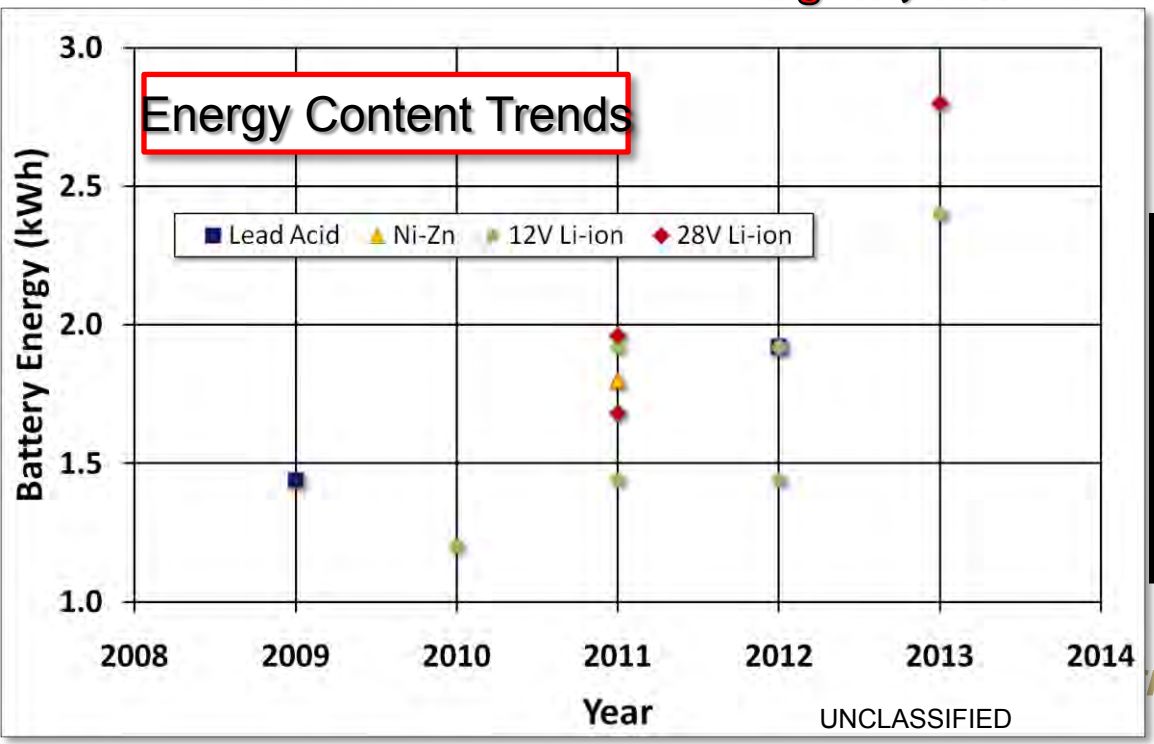
**Baseline**

**Advanced (Li-ion) 12V 6T Battery**
400-450W/kg
>$2000/kWhr

**Lighter, 33% More Energy**

**Li-ion Military Battery Pack Target**
>90Wh/kg
>920W/kg
<$500/kWhr

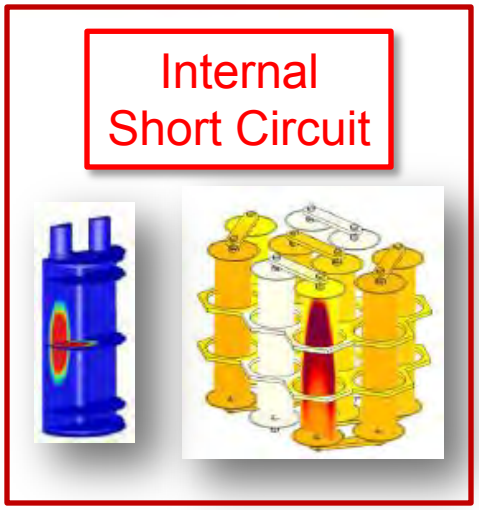
**2-for-1 Drop-in Replacement**
**½ Volume**




| Battery Technology | Advanced Battery Technologies Price Targets: Near-Term | Mid-Term Production | Long-Term High Volume |
|---|---|---|---|
| Lead Acid (12V) | $280/kWh | $250/kWh | $200/kWh |
| Ni-Zn (12V) | $500/kWh | $350/kWh | $200/kWh |
| Li-ion (12V or 28V) | $2,000/kWh | $1,000/kWh | $500/kWh |

# Li-ion Cell Failure Mechanisms

- **Field Failures:**
  - Unpredictable and Potentially Catastrophic
  - Typically Caused by Manufacturing Defects
    - Metallic particles/debris
    - Separator defect/damage
    - Other manufacturing issues
      - Electrode misalignment
      - Poor internal welds
      - Loose internal connections
- **Abuse Failures:**
  - Electrical
    - Overcharge / Overdischarge
    - External Short Circuit
  - Mechanical
    - Ballistic penetration
    - Crush, Nail penetration
  - Thermal
    - Overheating




# Ballistic Test Conclusions

- **Pack level testing carried out on Prototype Li-ion Packs (not designed to withstand ballistic impacts)**
  - Purpose: characterize worst case scenario during ballistic impact

- **The pack level ballistic testing indicate that battery designs must be developed to:**
  - Limit cell to cell and module to module thermal propagation during ballistic threats
  - Control/mitigate the release of toxic gases during ballistic threats
  - Balance the energy content and performance/safety requirements with Li-ion chemistry selection.

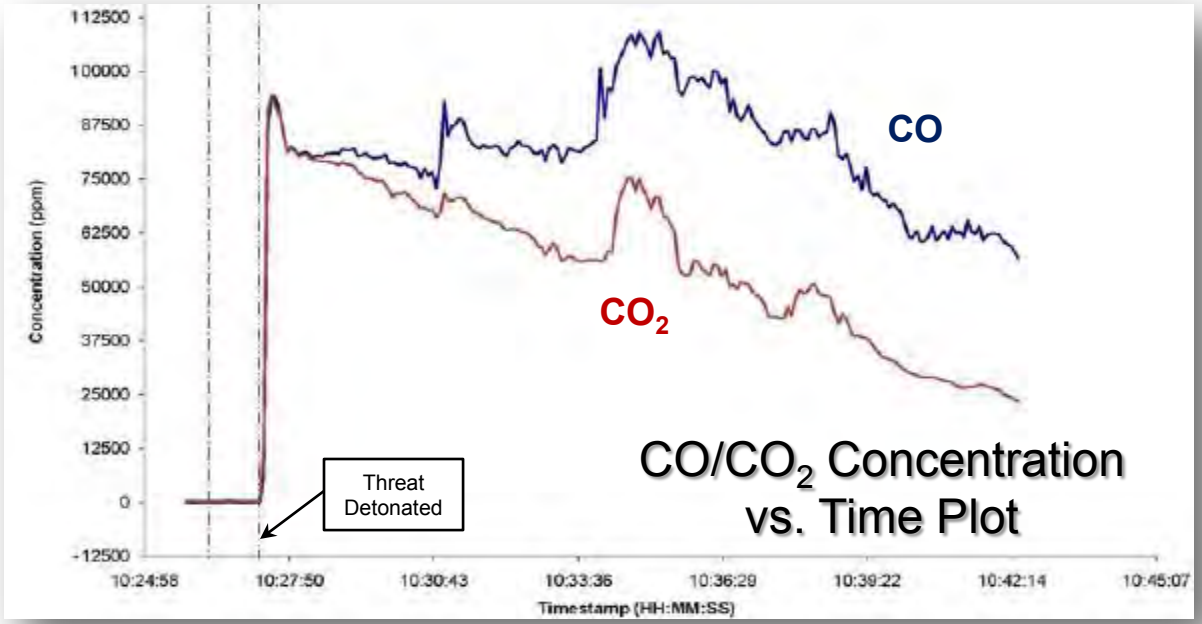
- **Additional areas of research:**
  - Development of new materials and technologies to optimize safety and performance during abuse conditions.
  - Improved cell/pack designs to improve safety during abuse testing.

# Ballistic Test Results
## Li-ion Pack Testing (NCA)

- **NCA Cell Chemistry**
- **173V, 6.4kWhr Pack**
- ***Prototype pack design*** **(to determine worst case scenario)**
- **125 ft$^3$ volume chamber**

| Analyte | Peak Concentration (ppm) | 15 min Average Concentration (ppm) |
|---|---|---|
| Carbon Monoxide (CO) | 108939 | 81588 |
| Carbon Dioxide ($CO_2$) | 94089 | 55651 |
| Methane ($CH_4$) | 16971 | 11445 |
| Ethylene ($C_2H_4$) | 3670 | 2497 |
| Formaldehyde (HC(O)H) | 8602 | 5347 |
| Methanol ($CH_3OH$) | 3771 | 2787 |
| Dimethyl Carbonate (DMC) | 21734 | 14307 |
| Methyl Butyrate (MB) | 47198 | 33368 |

Gas analysis via FTIR

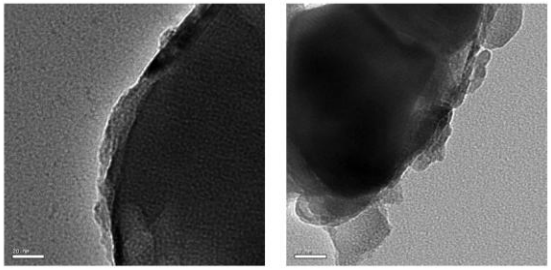



Max cell temperature: >750°C

# Small Business Innovative Research (SBIR) Programs

**History of Topics from 2009 to 2011:**

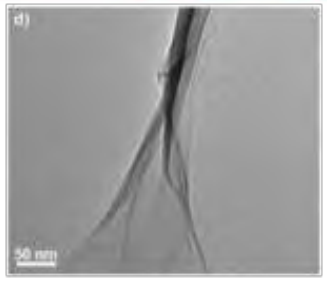
- **A093-175 – Development of Silicon Based Li-ion Battery Technology**
- **A093-178 – Development of High Power Rechargeable Li Batteries**
- **A093-200 – Advanced Battery Management System Development (including advanced prognostic and diagnostic capability)**
- **O092-EP7 – Enhancing the Utilization Efficiency of Cathode Materials in the Li ion Battery**
- **A102-124 – Lithium Ion Batteries with Wide Operating Temperature Range**
- **A102-138 – Development of Super-Capacitor with Improved Energy Density**
- **A102-139 – Lithium Air Rechargeable Battery**
- **A111-065 – Lithium Ion Battery Separator Development**
- **A112-116 – High Energy Cathode**



# University Projects

**University 1**

- Neutron Imaging of Lithium concentrations in Battery Cells
- Thermal modeling of Lithium ion batteries



**University 2**

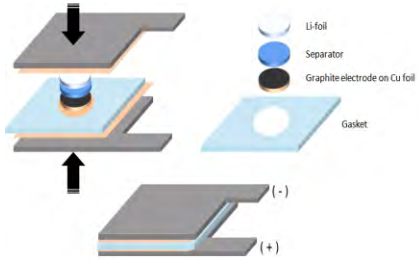
- Research study on novel carbonaceous anode materials (Graphene Nano-ribbons)
- First principals modeling of materials identified graphene edges as favorable for lithium intercalation

**University 3**

- Six research projects on: Ionic Liquid Electrolytes, Li-Air Catalysts, Graphene Electrodes, In-Situ observation of battery Cycling, Polymer Electrolytes, and Solid State Electrolytes

**University 4**

- Study of Lithium ion battery anodes to eliminate the formation of dendrites
- Development of ceramic electrolytes for safer lithium ion battery operation




**University 5**

- Study of the mechanisms of thermal runaway in lead acid VRLA batteries
- Research into methods for suppressing thermal runaway

# Battery Logistic Burden

## Lead acid Battery

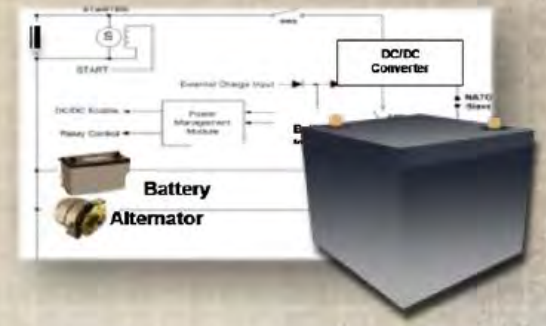
| | |
|---|---|
| Incorrect Voltage Output | 50% |
| Damaged - Transport Issues | 30% |
| Improper Electrical Performance | 20% |

**Approximately 80% of incorrect voltage failures were serviceable**

**Improved charging techniques can lead to 2X life improvement**


## Field Battery Maintenance & Training

## Improved Charging




## Battery Management

Battery represents one of the top 10 on-going maintenance cost in the theater

# It's All About The Warfighter

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.